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BOOK REVIEWS

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Causal Reasoning in Physics. Mathias Frisch. 264 pp. Cambridge U. P., New York, 2014. Price $95 (hardcover). ISBN 978-1-107-03149-4. (Marc Lange, Reviewer)

In an oft-quoted 1912 essay entitled "On the Notion of Cause," Bertrand Russell spoke for many twentieth-century philosophers in suggesting that classical physics had discovered the universe to be an acausal place: "The law of causality, I believe, like much that passes muster among philosophers, is a relic of a bygone age, surviving, like the monarchy, only because it is erroneously supposed to do no harm." In Russell's austere view, the laws of classical physics are merely relations holding among various physical quantities at various times. The laws do not portray certain of these quantities as causes of certain others. To regard acceleration, for example, as caused by force and mass would be to regard force as like muscular push or pull. The bare equations of physics are cleansed of any such anthropomorphic vestige and (generalizing Hertz's famous remark regarding Maxwell's electromagnetic theory) a given physical theory is just its system of equations.

Many philosophers since Russell's day have found many reasons to agree with Russell's view. Ordinarily, we think of causal relations as asymmetric (if c causes e, then e does not cause c), as favoring a certain direction in time (the future does not cause the past), and as presupposing a distinction between causes and background enabling conditions (as when the lighting of a match is caused by its being struck, not by its being surrounded by oxygen). Many philosophers have argued that the fundamental laws of non-quantum physics exhibit none of these features. Causal relations, then, would seem not to belong to the world that physics aims to describe. Rather, causal relations seem to be projected onto that world by us—perhaps as a reflection of the limited range of observations we can make, or perhaps because we inevitably approach the world with the intention of bringing about various outcomes we desire.

In his exciting new book, Mathias Frisch opposes the view that causal relations play no role in physics. According to Frisch (a philosopher of physics at the University of Maryland, College Park), causal relations, far from doing no harm, are an essential part of the way that non-quantum physics represents the world. Frisch argues that many of the inferences routinely made in physics would be impossible without causal assumptions. For instance, we observe points of light on various nights and infer that these points are the light emitted by stars. We could not draw this conclusion by feeding our nighttime observations into the laws of light propagation, since that calculation would require us to have data along an entire cross section of a forward light cone centered on the star being inferred. Rather, our inference exploits the idea that correlations among events standing in no direct causal relation are probably explained by the existence of a common cause of those events; in this example, the correlations are among our observations of the night sky at different times and from different terrestrial locations, and the star is the putative common cause.

Whether this argument from Frisch demonstrates that causal assumptions play an essential role in physics depends on whether the inference to the star's existence, for example, depends on causal assumptions. The inference clearly depends on the assumption that certain correlations would be extremely unlikely in the absence of a star. It is not yet evident to me, however, whether this assumption would be unwarranted in the absence of specifically causal assumptions.

Similarly, Frisch argues that although Maxwell's equations can be solved by both retarded and advanced potentials, the latter are routinely rejected on causal grounds: the correlated events required for incoming radiation from different directions of space to converge coherently onto an antenna, for example, lack a common cause. Frisch's argument here seems to be twofold. First, to reject advanced solutions as improbable, without any causal rationale for doing so, would be unwarranted. Second, the fact that the delicately correlated initial conditions required for advanced solutions are so unlikely can be explained by causal considerations (namely, that the initial states of a system's components are distributed randomly when they have no common cause in their past). But without these causal considerations, the requisite correlation's unlikelihood would have no explanation. It would simply be a brute fact—an unexplained explainer. Frisch includes an extensive, historically rich discussion of the debate between Einstein and Ritz on the arrow of radiation.

Of course, if one were inclined to regard physics as not being in the business of describing the world's causal relations, then (since many ordinary scientific explanations appeal to causal relations) one might be inclined to conclude that the relations of explanatory dependence traced by scientific explanations are likewise not objective features of the world that physics aims to describe. On this spare picture of the physical world, it might not be so implausible for the unlikelihood of certain sorts of correlations to have no explanation (and to be responsible for the usefulness of causal concepts in representing phenomena).

Alternatively, an "initial randomness" assumption might have an explanation other than that the initial states of a system's components have no common cause. Perhaps the "initial randomness" assumption could be explained instead by certain features of the very early universe. Frisch explores and critiques recent attempts to elaborate such a neo-Boltzmannian view of the origin of thermodynamic asymmetry.

Frisch surveys and responds to a wide range of arguments drawn from the recent literature in the philosophy of physics. His book will serve as an excellent introduction to this literature for new readers as well as a valuable, original perspective on that literature for those already familiar with it.

Marc Lange is Theda Perdue Distinguished Professor of Philosophy at the University of North Carolina at Chapel Hill. He does research on the philosophy of science and is the author of An Introduction to the Philosophy of Physics: Locality, Fields, Energy, and Mass (*Blackwell, 2002*).

Tensor Calculus for Physics. Dwight E. Neuenschwander. 238 pp. Johns Hopkins U. P., Baltimore, MD, 2015. Price $45 (paper) ISBN 978-1-4214-1565-9. (Franco Battaglia and Thomas F. George, Reviewers.)

An introductory *Tensor Calculus for Physics* book is a most welcome addition to the libraries of both young students in physics and instructors with teaching duties at the advanced undergraduate level. Indeed, the literature on the subject, notwithstanding how ample it is, lacks books that are both at an introductory level and have young physicists as a preferred audience. Professor Neuenschwander's book fills the gap in robust fashion.

The book comprises eight chapters and may be ideally divided into two parts, with the first five chapters containing the core of the subject. Besides reviewing some basics in vector calculus, Chapter 1 explains very clearly how the need for physical quantities to have a tensor character arises. In this way, rather than defining tensors as multicomponent entities with a specific transformation law under a coordinate transformation, the concept is very appropriately introduced as a necessary requirement to represent physically meaningful quantities. The chapter is probably longer than what would be necessary, and some of the examples presented with a clarifying aim might not be a best choice (see, e.g., the example of the transformation between inertial frames of the electric and magnetic fields in Sec. 1.8), yet it is a good starting point for readers who would use the book as a self-study tool. Moreover, the exercises at the end of the chapter have been very well chosen for the intended level.

With enough motivation from Chapter 1, Chapter 2 considers some of the higher-rank tensors that undergraduate students might have encountered in their introductory courses: the inertia tensor from mechanics courses and the electric susceptibility, the electric-quadrupole, and the electromagnetic-stress tensor from E&M courses. Regrettably, the author omits the deformation tensor arising from applying a stress to solid bodies: the three-dimensional deformation of a rubber band when it is stretched along a single direction is perhaps a very effective example of the emergence of higher-rank quantities. Again, the exercise collection is well chosen, although here some of the exercises are more advanced than expected (see, e.g., ex. 2.17, which requires a non-trivial familiarity with quantum mechanics).

In Chapter 3 and 4, the author does a superb job in presenting the all important metric tensor, to which a detailed treatment is devoted, and the covariant derivative, quite well motivated and explained. Both chapters are equipped with very doable and instructive exercises. Finally, the last chapter of the core of the subject prepares the path for applying the theory to general relativity, a step taken in Chapter 6, where the basic theory is applied to electrodynamics as well, at a level well weighted for the intended audience. An excellent chapter is the last one (Chapter 8), where the reader is beautifully and gently introduced to the more advanced differential forms, which is how the subject should be eventually mastered when the readers reach a higher level.

Chapter 7 puzzles us in that the material covered there, especially the dual vector space and dual vector bases, could have fit perhaps better in a chapter between the first and the second. The idea that a scalar product is performed between two vectors belonging to different spaces, one dual to the other, should be conveyed as early as possible, together with the clarification of self-duality of Euclidean space parameterized by an orthonormal basis.

Given the level of the book, having solutions to the exercises at the end would have been helpful for the reader, as well as comments on the discussion questions that the author poses at the end of each chapter.

As a last remark, the author might consider in a subsequent edition of the book the use of Schouten's notation, according to which the primes denoting the "primed" coordinate frame are attached to the component index rather than to the kernel letter denoting a multicomponent quantity, say $A_{k'}$ rather than A'_k. This is a matter of taste, but our experience suggests that Schouten's notation is much more effective when, upon performing algebra where several multi-indexed quantities are involved, keeping track of the indices might become somewhat frustrating, especially for the novice.

Apart from some minor criticisms, we think that the book, which starts from the very basic and goes on gently up to fairly advanced material, deserves the best attention by both young physicists and instructors.

Franco Battaglia is professor of chemical physics at the Department of Engineering Enzo Ferrari, University of Modena, Italy. He has been active in several fields of theoretical chemical physics: molecular scattering theory, atom-surface interactions, phase transitions in 2D systems, and many-body theory. He has coauthored two books in classical and quantum physics and in chemical physics. In collaboration with Professor T. F. George, he has proposed a guideline (published in AJP in 2013) for effective teaching of tensor calculus at the advanced undergraduate level.

Thomas F. George has served as chancellor at the University of Missouri-St. Louis since 2003, and prior to that he was chancellor for seven years at the University of Wisconsin-Stevens Point. As professor of chemistry and physics, he maintains an active research program in chemical/materials/laser nanophysics, including nanomedicine. His work has led to 760 papers, 5 authored textbooks, and 18 edited books/volumes. He is also a jazz pianist performing throughout the St. Louis region, and his performances have extended to Illinois, Arkansas, and overseas to China, Croatia, Hungary, Kuwait, Romania, and Serbia in connection with his travels as chancellor and scientist.

Lectures on Quantum Mechanics. Steven Weinberg, 377 pp. Cambridge University Press, New York, 2012. Price \$89.99 (hardcover). ISBN 978-1-107-02872-2. (Harsh Mathur, Reviewer.)

The publication of Steven Weinberg's *Lectures on Quantum Mechanics* is a cause for celebration. Young readers learning quantum mechanics are fortunate to have this volume. So, for that matter, are those of us who teach it.

The book is intended to accompany a one-year introductory graduate course in quantum mechanics. At 375 pages it has brevity not achieved since Dirac's *Principles of Quantum Mechanics* (314 pages, 4th edition, Oxford University Press). Dirac's is one of the great books in the history of human civilization. But after four score and more years it is beginning to age. The appearance of a new book by a scientist of Weinberg's stature is thus well timed. The explicitly pedagogical intent of Weinberg's book sets it apart from books written by other great masters. Although concise it is written with the exceptional clarity and logic that readers would expect of Weinberg.

Any textbook on graduate quantum mechanics is an exercise in selectivity. Although there are no universal selection rules, the choices Weinberg has made are quite conventional. What is distinctive about this book is not the choice of topics, but the treatment of those topics and the illustrative examples.

The first three chapters introduce quantum mechanics. Chapter 1 is on history, Chapter 2 on simple applications of the Schrödinger equation, and Chapter 3 on the general principles.

Reading Weinberg's historical introduction may be the next best thing to reading the original papers. Points that are normally glossed over, such as Bohr's use of the Correspondence Principle to deduce that the quantum of angular momentum is $h/2\pi$, are elucidated. The account of Heisenberg's exploits, while recovering from hay fever on the North Sea island of Helgoland, is absolutely riveting. But the description of Schrödinger's work falls comparatively flat as Weinberg succumbs to the temptation of giving a schematic account of how it could have been done instead of telling us how it was actually done.

In Chapter 3, Weinberg sets forth the general principles of quantum mechanics. A distinctive feature of his presentation is the importance given to symmetry principles, which allows him to downplay and postpone discussion of the canonical formalism. When he does return to the canonical formalism in Chapter 9, he gives an excellent account of it, including both Feynman path integrals and Dirac's theory of constraints (a subject not normally covered in books at this level, although it should be). Perhaps the most unusual feature of Chapter 3 is the discussion of the measurement principle. More space is devoted to alternatives to the Copenhagen interpretation than to the Copenhagen interpretation itself, and Weinberg concludes that the problems with interpretation might be telling us to look for a more satisfactory theory that supersedes quantum mechanics itself.

The remainder of the book applies quantum mechanics. Chapter 4 is concerned with angular momentum, spin, statistics, and further development of symmetry. Chapters 5 and 6 are concerned with approximation methods (perturbation theory, variational principle, WKB approximation, adiabatic approximation). The two short chapters on scattering theory are particularly masterful. Chapter 7 is the scattering theory I normally teach in such a course; Chapter 8 is the scattering theory I wish I taught. Chapter 10 deals with particles in electromagnetic fields including discussion of gauge invariance, Landau levels, and the Aharonov-Bohm effect. Chapter 11 is on Quantum Electrodynamics; field quantization is dealt with here with unusual sophistication. The final chapter is on entanglement and an appropriately brief introduction to quantum computing.

Weinberg is interested in explaining natural phenomena. Marvels abound in every chapter. In less than one page he explains the shell model of nuclei and how to calculate the first few magic numbers (Chapter 4). Also in Chapter 4 is an enthralling six-page introduction to the symmetries of elementary particles, and the hidden SO(4) symmetry of hydrogen. Time-dependent perturbation theory is applied to calculate the ionization of atoms (Chapter 6). The Low equation and shallow bound states are introduced in Chapter 8 and the formalism is applied to proton-neutron scattering. Also in Chapter 8 is a brief intuitive explanation of the Froissart bound and its latest tests at the Large Hadron Collider and the Pierre Auger observatory. Deep ideas like broken symmetry and effective theories appear in Chapter 5. If you teach quantum mechanics you have probably struggled for years to incorporate similar material in your course. And in this book you will find many of the things you have only attempted, all beautifully and fully realized. One of the strengths of the book is its bibliography that allows the student to see quantum mechanics as a living, growing subject.

Knowledgeable readers sometimes carp about the nonstandard notation that pervades all of Weinberg's books. Generally, this criticism seems misplaced because Weinberg always explains his notation meticulously. A rose by any other name is still a rose. But in this book Weinberg ups the ante by eschewing Dirac's bra-ket notation because "for some purposes it is awkward." Weinberg's notation is in fact well adapted to discuss concepts that Dirac notation obfuscates such as operator adjoints. In Weinberg's notation, which is also used in more mathematically-oriented books, $\langle\varphi|\psi\rangle$ is written as (φ, ψ). Thus, $\langle\varphi|A|\psi\rangle$ must now be unambiguously written as either $(\varphi, A\psi)$ or $(A^{\dagger}\varphi, \psi)$. However, Dirac notation is better at conveying the operator character of outer products, at constructing resolutions of the identity, for formulating path integrals, and much else. Dirac notation is also typographically beautiful and emblematic of quantum mechanics. More pragmatically, it is the notation used in the literature including Weinberg's field theory books. Instructors using this book will likely adopt a middle ground using Weinberg's notation where it is evidently superior while making sure their students remain fluent in Dirac's notation.

One topic that Weinberg skips without regret is the relativistic Dirac theory. He explains his distaste for the subject in the preface to this book and at greater length in volume 1 of his field theory book (*The Quantum Theory of Fields,* vol. 1, Cambridge University Press, 2005). Essentially, his point is that the idea of holes and the Dirac sea does not apply to bosons and that some of the original motivation for the work was based on misunderstandings. It has become the norm to omit this subject in quantum field theory books in favor of alternative formulations. But its absence in a quantum mechanics text is regrettable; the hole theory does apply to fermions even if not to bosons. Historically it not only provided the first explanation of anti-matter, it also led directly to the understanding of p-type carriers in semiconductors, a discovery that has transformed the way we now live. The Dirac equation and hole theory remain the basis of some of the most interesting work in condensed matter physics today on materials like graphene and topological insulators. In the condensed matter analogs the Dirac sea has an undeniable reality. But readers of this book will have to look elsewhere to learn the Dirac equation.

The twelve chapters of the book are divided into a total of 78 sections. With reasonable elisions a one-year course would need to proceed at the brisk but attainable pace of two sections per week. The table of contents enumerates the topics covered in each section. As in Weinberg's other books square boxes are used to separate successive topics; the reader who is able to check all these boxes will be well educated indeed. In many respects Weinberg goes deeper and farther into the subject than other comparable textbooks. His book will appeal to precocious and ambitious students. But other students may find the standard texts more accessible. There are some nice problems that accompany each chapter but instructors will almost certainly have to augment that pool with additional problems. There are few subjects in physics where figures are more dispensable than graduate quantum mechanics but inexplicably some reviews have still complained about the absence of figures in this book.

Regardless of whether it is widely adopted as a graduate text, Weinberg's book is a magnificent resource. It will educate and inspire generations of physicists. It sets forth what Steven Weinberg believes students should know about quantum mechanics. Anyone who is serious about the subject should pay heed.

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Nonlinear Optics and Photonics. Guang S. He. 648 pp. Oxford U. P., New York, 2015. Price: $89.95 (hardcover) ISBN 978-0-19-870276-4.

Structure and Interpretation of Classical Mechanic, 2nd ed. Gerald Jay Sussman and Jack Wisdom. 575 pp. MIT Press, Cambridge, MA, 2014. Price: $85 (hardcover) ISBN 978-0-262-02896-7.

Introduction to General Relativity, Black Holes, and Cosmology. Yvonne Choquet-Bruhat. 299 pp. Oxford U. P., New York, 2015. Price: $44.95 (paper) 978-0-19-966646-1.

The Story of Collapsing Stars: Black Holes, Naked Singularities, and the Cosmic Play of Quantum Gravity. Pankaj S. Joshi. 238 pp. Oxford U. P., New York, 2015. Price: $49.95 (hardcover) ISBN 978-0-19-968676-6.

Theory of Inelastic Scattering and Absorption of X-Rays. Michael van Veenendaal. 245 pp. Cambridge U. P., New York, 2015. Price: $95 (hardcover) ISBN 978-1-107-03355-9.

Transition Metal Compounds. Daniel I. Khomskii. 497 pp. Cambridge U. P., New York, 2014. Price: $125 (hardcover) ISBN 978-1-107-02017-7.

Amorphous Semiconductors. Sándor Kugler and Koichi Shimakawa. 158 pp. Cambridge U. P., New York, 2015. Price: $99.99 (hardcover) ISBN 978-1-107-01934-8.

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